Zero-degree high-precision hadronic calorimetry

A proposal for Generic Detector R&D for an Electron Ion Collider

Pi and Co-PIs:

John Hauptman (PI)
Physics Department and Ames Lab
Iowa State University
Ames IA, 50011
hauptman@iastate.edu

Pawel Nadel-Turonski (co-PI for JLab)
Jefferson Lab
12000 Jefferson Ave
Newport News, VA 23606
turonski@jlab.org

Charles Hyde (co-PI for ODU)
Old Dominion University
Dep't of Physics
4600 Elkhorn Ave
Norfolk, VA 23529
hyde@jlab.org

Stephen Bueltmann
Old Dominion University
Dep't of Physics
4600 Elkhorn Ave
Norfolk, VA 23529
sbueltma@odu.edu

Abstract

Hadronic calorimetry is a key component of the EIC detectors. A far forward 'Zero Degree Calorimeter' (ZDC), primarily for neutrons, is critical for a number of important physics programs at the EIC. Many of these topics would benefit from state-of-the-art hadronic calorimetry. The Dual REAdout Module (DREAM) technology was previously under development for the ILC and is currently a generic R&D project at CERN. This technology offers the prospect of 3% energy resolution for 100 GeV neutrons. John Hauptman (PI) is a member of the CERN RD52 collaboration. He has invited the co-PIs to join this effort.

We propose a one-year exploratory project to answer the following question: *Are there aspects of the application of the DREAM concept to an EIC ZDC that require EIC-specific R&D?*. Our budget request is $32,100 for FY2015. This is for travel, primarily to CERN for beam tests of DREAM modules currently under construction at Iowa State University.

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1 Introduction

We propose first-year participation in CERN beam tests of high-precision hadronic calorimetry for the zero-degree region of an Electron-Ion Collider (EIC). If successful, we will propose further work on a specific design tailored to the physics objectives and requirements for an EIC, and develop manufacturing techniques for easy and lower-cost construction of larger modules.

The RD52 Project at CERN is a pure instrumentation experiment [1] without reference to any current or future detector. The goal is to develop high-precision hadronic calorimetry by understanding the fundamental limitations to energy resolution and linearity in hadronic energy measurements up to the highest energies. Based upon CERN RD52 data and our understanding of the complexities of hadronic calorimetry, hadronic energy resolutions near 1-2% at high energies are expected, including constant terms. For the high energy neutrons expected in the forward region at an EIC around 100 GeV, the energy resolution expected is about

$$\sigma/E \sim 3\%.$$

The initial focus of the Jefferson Lab effort would be participation in the CERN beam tests of existing Pb-absorber and Cu-absorber modules in December 2014, and the subsequent testing of a larger Cu-absorber module in the summer of 2015. This larger module is 16 times the size of each of the existing nine Pb and two Cu modules and therefore will be a more definitive test of dual-readout calorimetry without the substantial ($\sim 4\%$) leakage fluctuations that have limited the overall energy resolution of previous tests.

This large module is also a good prototype for a 1-meter diameter calorimeter at an EIC, and also a good prototype to understand the design, construction and assembly issues for a larger module.

The RD52 group is responsible for the design and manufacture of a larger copper-absorber module by a new technique, developed in collaboration with the Ames Laboratory (US DoE), by rolling the copper shape with fiber grooves to a precision of microns over a span of 2.5 meters. This construction is being done at ISU and will be completed in time for the summer 2015 test beam.

The modules that we have built and tested are listed with their absorber, mass, and estimated leakage in the table.

Test module	abs-orber	mass	leakage fluctuations
DREAM module	Cu	1.00 ton	$\sim 4\%$
Pavia module	Pb	0.15 ton	-
Pisa module	Cu	0.12 ton	-
Nine Pavia modules, 3×3	Pb	1.35 ton	$\sim 4\%$
Two Pisa modules	Cu	0.24 ton	-
Ames module	Cu	1.92 ton	$\sim 3\%$
Pb/Pavia + Cu/Pisa + Cu/Ames	-	3.51 ton	$\sim$ 1-2%
plus, surrounded with 0.5-ton			
of plastic scintillator		4.00 ton	$\sim 0.5\%$

In order for us to demonstrate an energy resolution near 1-2%, we will need to reduce leakage fluctuations to less than 1%, and we are aiming to achieve this in the summer 2015 beam test.

2 Zero Degree Calorimetry in an Electron Ion Collider

Many aspects of hadronic calorimetry are generic to different experiments. Nonetheless there are a number of aspects of the physics program of an EIC that merit special attention to the performance of a Zero Degree Calorimeter (ZDC), particularly for neutrons. In an EIC an ion species ${}^{A}Z$ has total momentum ZP_0, where P_0 is the momentum a proton would have stored in the same lattice. Spectator or evaporation neutrons produced in eA collisions will have typical longitudinal momenta *circa* Z/AP_0. For $N = Z$ nuclei, this is 1/2 of the nominal proton momentum P_0, and for a heavy nucleus, *e.g.* ^{208}Pb, $p_n \sim 0.4P_0$. Thus for $P_0 = 100$ GeV/c, spectator neutrons will have momenta from 40 to 50 GeV/c depending upon Z/A and for $P_0 = 200$ GeV/c the spectator neutrons will have momentum up to 100 GeV/c. Another interesting case is spectator neutrons from a proton beam. This will occur *via* the Sullivan process, in which a DIS, or SIDIS, or Deep Virtual Meson Production (DVMP) process happens on the π^+ cloud of the proton. In this case the spectator neutron will have momentum up to the full proton beam momentum. Thus, rather than detecting a jet of particles (mostly pions), each of order ≤ 10 GeV, we need to detect individual neutrons at energies up to ~ 200 GeV.

The IP/accelerator integration of the JLab/EIC design has full acceptance of zero degree neutrons up to 15 mrad relative to the ion beam direction at the IP. A ZDC will be placed 40 m downstream of the IP, with approximately 1m separation from the ZDC center to the ion beamline. This allows sufficient space for a $15\,\mathrm{mr} \times 40\,\mathrm{m} = 0.6$ m radius ZDC, plus additional radius to contain lateral spread. The proposed eRHIC ZDC, as presented at the EIC Users Meeting this week at SUNY Stony Brook has an acceptance of ≥ 5 mrad around the ion direction.

Some explicit physics channels, and their detector requirements are enumerated next.

- Spectator neutron tagging in $\mathrm{D}(e,e'n_S)X$ (and SIDIS, DVCS, DVMP) processes. This process is the isospin twin to spectator proton tagging: $\mathrm{D}(e,e'p_S)X$. The latter reaction is a powerful probe of neutron structure, as the forward proton momentum tags the initial momentum and virtuality of the active neutron. This enables the mapping of the neutron structure as a function of the neutron momentum in the np wavefunction of the deuteron. It is expected that at sufficiently low np relative momentum, the neutron and proton are essentially free, whereas at sufficiently high np relative momentum, the np pair are in a highly correlated short distance interaction. Recent evidence suggests that the EMC effect in nuclei is dominated by these high-momentum np pairs in nuclei [2]. The virtue of neutron tagging is that it allows the analog measurement of bound proton structure. This process places very stringent requirements on the energy and angle resolution of the ZDC. A sensitive test of the nuclear structure effects of the proton bound in the deuteron requires energy resolution on the same order as the intrinsic momentum distribution of the deuteron. If $30\%/\sqrt{E}$ can be achieved for 50 GeV neutrons, this translates to 4.2% energy resolution. Boosted back to the deuteron rest frame, this is a tagged proton longitudinal momentum resolution of $\sim$ 40 MeV/c. This resolution would allow the first ever mapping of tagged bound protons in the deuteron, as illustrated by the deuteron momentum distribution of Fig. 1. The transverse momentum resolution tagging will be even better. With 1 cm rms spatial resolution at 40 m, this translates to a rest frame relative momentum of 12.5 MeV/c.

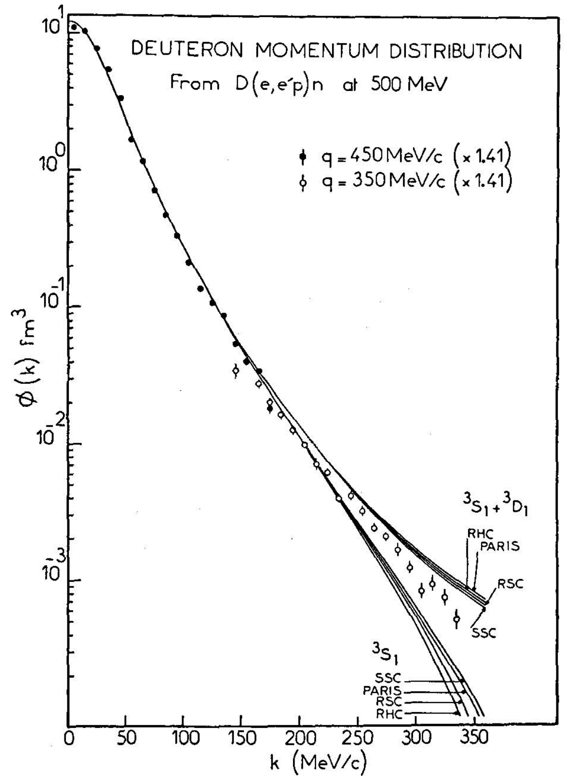

Figure 1: The np momentum distribution in the deuteron.

- Spectator neutron tagging in $^3\mathrm{He}(e,en_S)X$. If ^{3}He (both polarized and unpolarized) is used as a proxy for a neutron target, then forward neutron tagging is a veto on active proton events (compared to active neutron events, that will have either a lower momentum or high $p_\perp$ neutron in the final state). Forward neutron tagging is also a veto on dp final states, in *e.g.* exclusive processes on the quasi-free neutron. The 15 mrad aceptance of the JLab/EIC design allows tagging of neutrons with transverse momentum up to 1 GeV/c for a 200 GeV/c ^{3}He beam.

- Neutron evaporation in nuclear DIS. In a DIS event on a nucleus, one or more nucleons are knocked in the fragmentation of the spectator partons, with additional nucleons possibly knocked out by the current jet fragmentation. The residual nucleus is left, on average, in a highly excited state, which will thermalize and cool primarily by evaporating neutrons. With typical energies in the nuclear rest frame of 5 MeV, or momenta 100 MeV/c, these neutrons will be emitted in a forward cone of typical size (for a heavy nucleus and $P_0 = 100$ GeV/c)

$$\theta_n(\text{Evaporation}) \sim \frac{(0.1\,\text{GeV/c})}{(Z/A)P_0} \approx 2.5\,\text{mrad}. \tag{1}$$

  The ZDC will have excellent acceptance for these neutrons. At 40 m, individual neutrons will be separated by $\sim$ 10 cm and can be individually resolved. The exciting possibility, not yet fully elaborated theoretically, is that this forward neutron multiplicity could be used event-by-event to establish something akin the centrality in nucleus-nucleus collisions. This would allow the study of fragmentation as a function of nuclear depth in a single ion species, and not just as a function of A.

- Break-up veto for exclusive processes on nuclei. Exclusive processes on nuclei, such as ${}^AZ(e,e'\phi)^AZ$ offer the fascinating possibility of mapping the transverse spatial density of gluons in nuclei. However, this requires accurate determination of the exclusivity of the reaction. In some portion of the phase space, the scattered ion can be detected directly. In other cases, exclusivity must be determined by vetoing on nuclear excitation. A dominant excitation-decay mode will be excitation of the Giant Dipole Resonance, followed by emission of a $\sim$ 10 MeV (or 150 MeV/c) neutron. A forward neutron veto will be essential for this physics program.

Our exploratory R&D project will allow members of the EIC community to join the state-of-the-art CERN RD52 calorimetry project. This initial year will permit us to determine what unique aspects of hadronic calorimetry at the EIC might require more in-depth development.

3 High performance hadronic calorimetry

A direct raw energy resolution of

$$\sigma/E \approx 32\%/\sqrt{E} \oplus 1\% \qquad \text{(for both jets and single hadrons)}$$

was achieved in the SPACAL calorimeter [3] many years ago, and it depended upon neutron compensation to attain equal hadronic and electromagnetic mean energy response, which in turn required a 20-ton Pb scintillating-fiber calorimeter with readout extending out to a few hundred nanoseconds, and a small sampling fraction. Therefore, this design was never used in a collider experiment (calorimeter volume too large and readout time too long). However, it was an epochal achievement in particle instrumentation, and was the experimental demonstration of "compensation" by Wigmans [3].

Wigmans [4] (and others, [5]) realized that compensation could be achieved dynamically, event-by-event, by separately measuring the electromagnetic part (with quartz fibers that collected only Čerenkov light from relativistic electrons and positrons) combined with scintillating fibers that collect light from all charged particles of the shower, including protons from $np \to np$ scatters, spallation protons, and neutrons from nuclear break-up . This is "dual-readout" and it was successfully demonstrated by Wigmans, Akchurin, Hauptman and Paar in 2005 [6]. This Dual REAdout Module (DREAM) was very small (one ton of Cu) with energy resolution limited to 4% by lateral leakage fluctuations. The DREAM module and each RD52 module is 10 λ_{int} deep, and therefore essentially all leakage is lateral and, we believe, consisting mostly of neutrons. Since the number of MeV-energy neutrons was very large, the energy response was perfectly Gaussian, as expected from the Central Limit Theorem.[1] The principle of dual-readout was decisively and clearly demonstrated.

This original work has now become an official part of the CERN program as Project RD52 [1], for which Wigmans has received DoE Detector R&D funding for three years to support beam tests, infrastructure, fibers, PMTs, *etc.*, for the INFN-built Pb and Cu modules, plus a large Cu module (2-ton). Stacked together, these modules would constitute SuperDREAM (with mean leakage of only 1%, and would include many technical improvements over the small and simple DREAM module [1]a.

3.1 Dual-readout calorimetry

The complex development of a hadronic shower can be usefully described as two parts: (1) the production of π^0 and η^0 mesons which promptly decay to photons, and (2) everything else. Everything else includes energetic $\pi^{\pm}, K^{\pm}$, spallation protons, slow Fermi-energy neutrons, energetic recoil nucleons, other hadrons from the nuclear breakup, α particles, fission and other nuclear fragments. In our beam tests, we calibrate each calorimeter tower with electrons, and therefore the response to electron-initiated showers within the calorimeter is one, denoted by (e) for electromagnetic response. The response of all the rest, the non-electromagnetic part, is called (h) for

[1] There is considerable confusion within the CALICE collaboration about the nature of leakage from calorimeters. The CALICE collaboration has built a number of modules with depths of 4.5-5.5 λ_{int}. These calorimeters leak, typically, high energy particles longitudinally out the back and, therefore, the energy response shows an extreme low-side tail, sometimes extending down to one-half the incident beam energy. It is important that these two very different forms of calorimeter leakage, lateral (RD52) and longitudinal (CALICE), not be confused.

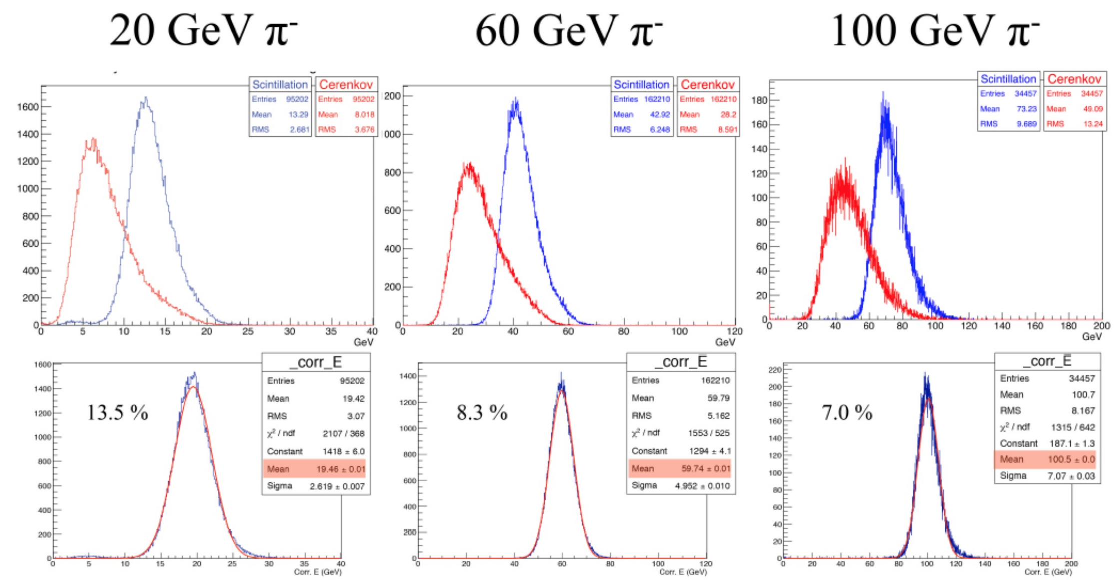

Figure 2: π^- beam data at 20, 60, and 100 GeV. Upper row, raw responses of the scintillating fibers, S (blue), and the Čerenkov fibers, C (red). Lower row: the dual-readout response from Equs. 2-3. Calibration was with electrons into the center of each tower. The dual-readout response is Gaussian and linear, although the energy resolution is still limited by lateral leakage fluctuations.

hadronic response. The individual components of h vary in their responses from zero to more than one.

The ratio of the electromagnetic to the non-electromagnetic part is commonly called "e/h"; we use the inverse of this as the variable $\eta = h/e$, which for almost all calorimeters is less than one, and for highly non-compensating calorimeters, *e.g.*, crystal and quartz fiber calorimeters, can be as small as $\eta \approx 0.20$. For an electromagnetic fraction, f_{EM}, the differing scintillation and Čerenkov responses can be written [6, 7] as

$$S = E_{\mathrm{hadron}}\ [f_{EM} + (1 - f_{EM})\ \eta_S] \tag{2}$$

$$C = E_{\mathrm{hadron}}\ [f_{EM} + (1 - f_{EM})\ \eta_C]. \tag{3}$$

Recent data in the Pb-absorber modules from our recent test are shown in Fig. 2 for incident π^- beam energies of 20, 60, and 100 GeV. The upper row shows the scintillator response, S, and the Čerenkov response, C, both non-Gaussian, both skewed, and both at the wrong energy. This is what you expect from ordinary, sampling calorimeters with scintillation or Čerenkov readout. The dual-readout response is shown in the lower row of Fig. 2, it is perfectly Gaussian[2] and limited in resolution only by lateral leakage fluctuations.

[2]Gaussian response means that the Central Limit Theorem is on your side; most hadron calorimeters are *not* Gaussian in their response.

The linearity of a calorimeter in a physics experiment is even more important than good Gaussian resolution. The linearity of this module is shown in Fig. 3, and we have found similar linearity in the original DREAM module. Absolute energy linearity is essential for a modern high energy collider. We have easily achieved this in beam tests.

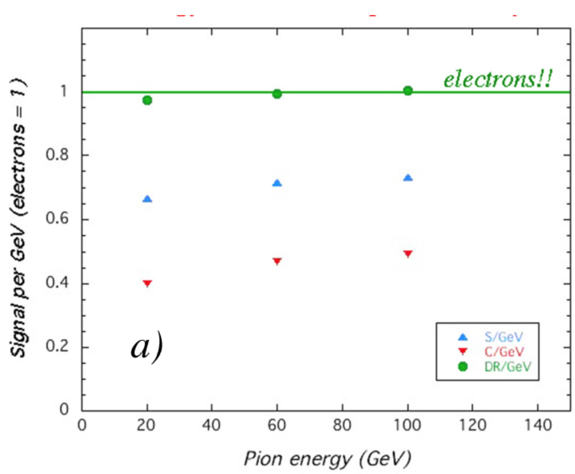

Figure 3: The response linearity from 20 to 100 GeV for the new superDREAM modules. We found similar excellent linearity in the original DREAM module.

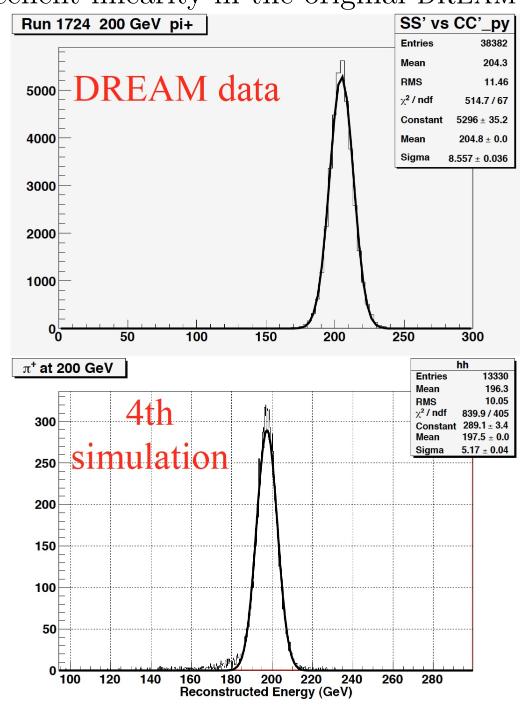

Figure 4: The DREAM data and a corresponding FLUKA simulation, both for π^+ beam at 300 GeV.

We tested the DREAM module with a BGO array of 100 crystals in front and read out in dual-readout, plus an array of plastic scintillators surrounding DEAM to sample the neutrons generated in the hadronic cascade, and this leaked energy is included in the energy sum that is plotted, thus mitigating the leakage fluctuations to below $\sim$ 4%. A thorough study of neutrons in these dual readout calorimeters is given in Refs. [12, 13, 14, 15]. The data therefore suffer less than the full $\sim$ 4% lateral leakage, and this can be seen in the data, shown in Fig. 4 in the top figure. In the BGO front section, the scintillation and Čerenkov light were easily separated in the time domain, since the Čerenkov light comes within a nanosecond and the BGO scintillation light has a lifetime of 300 ns. The response is a perfect Gaussian with a resolution of 4.2%.

The lower plot is a FLUKA simulation of a very similar configuration, the 4th concept detector [11], in a 4π detector, and therefore with low leakage fluctuations. Clearly, the simulation in a full detector has less leakage and therefore better resolution. These are shown in Fig. 4 for a direct comparison to data. The 4th simulation with a 4π calorimeter system achieved about 2.3% energy resolution at 300 GeV.

One small detail: the data show no low-side tail since the DREAM module is exactly uniform in volume. The simulation, however, had non-projective fibers and edges to trapezoidal modules, thereby incurring a loss of signal at the boundaries between modules.

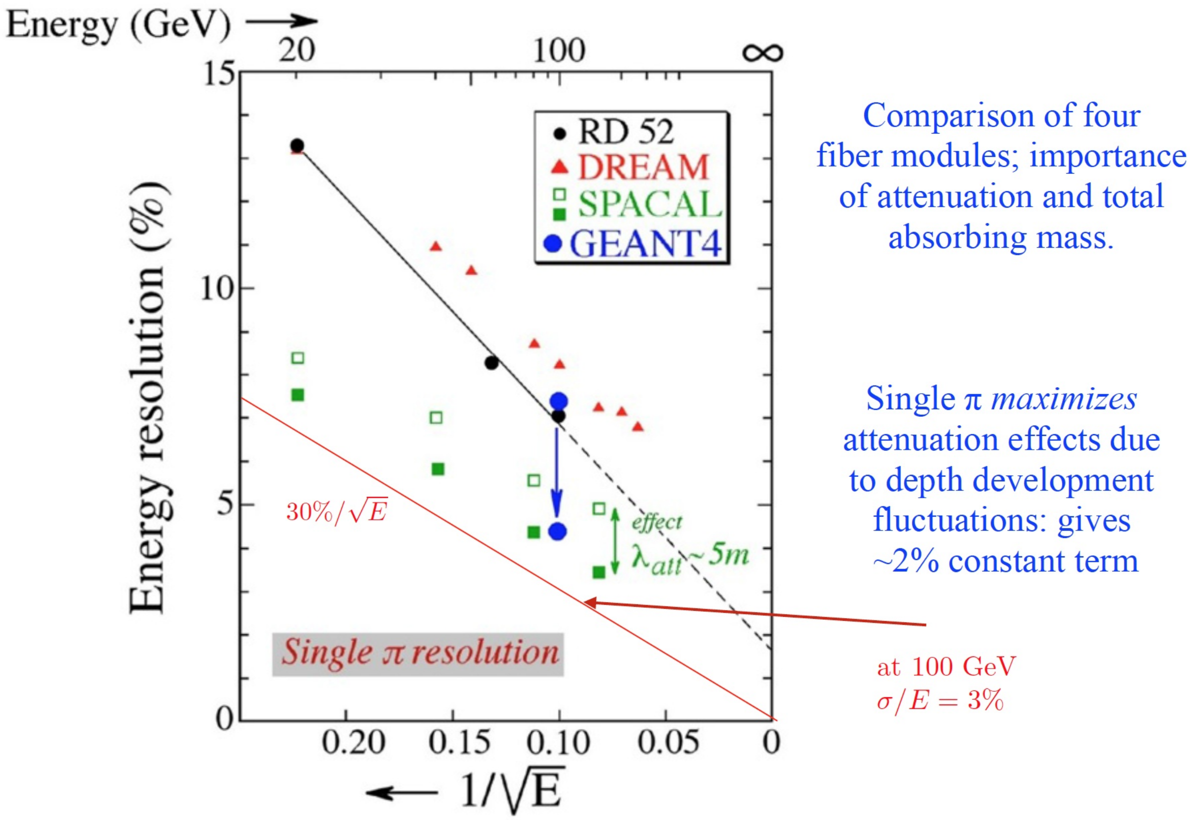

Figure 5: Fiber calorimeter data from SPACAL, DREAM, RD52 and GEANT4 simulation of RD52 modules. The blue solid dots are GEANT4 simulation of a 3×3 Pb-module and its improved performance as a 7×7 Pb-module. The resolution for $\sigma/E \sim 30\%/\sqrt{E}$ is shown as the thin red line, and the effects of optical attenuation in the scintillating fibers is indicated for the SPACAL module. All data and simulations are for single incident π^-.

Data from several fiber calorimeter modules are shown in Fig. 5 for SPACAL, DREAM, and RD52 (including GEANT4 simulations of larger arrays, 5×5 and 7×7 modules, to assess the effects of larger absorber masses [16]). The thin red line is an energy resolution of $\sigma/E = 30\%/\sqrt{E}$, and we are closing in on this goal.

3.2 Construction of a Cu module

The DREAM proposal [8] that supports the completion of 4-5 tons of Pb-absorber and Cu-absorber modules will be completed with the construction of the large module in order to achieve a total mass of approximately 4 tons.

Therefore, the highest priority will be the perfection and execution of the copper rolling to produce a number of Cu-modules in Ames with the technical expertise at the Ames Laboratory [9], a small high-quality US DoE lab that specializes in heavy metals and critical rare earth materials. We have test rolled small samples with exacting precision, Fig. 6, and also samples as large as $20 \times 60\text{cm}^2$ with this shape. We believe a different alloy will improve the rolling; then we can manufacture a stack of plates for a whole module.

We will introduce optical quality control going beyond what has been done previously in order to attain good light collection uniformity. The upstream ends of the scintillating fibers will be blacked with 100% absorbing epoxy. This prevents backward-going scintillation light from the shower being reflected by imperfectly cleaved fibers and returning to the scintillator PMTs. The upstream ends of the Čerenkov fibers will be mirrored. This will reflect the fraction of backward-going Čerenkov light so that the C signal will be two images of the shower in depth: the direct light image and the reflected light image. This has three direct benefits:

1. the Čerenkov photoelectron signal is increased;
2. the time difference between the images measures the depth of the light production in the calorimeter, and this information is further used to correct for the attenuation in the scintillating fibers. This has been shown to work [6, 1] and it suppresses a constant term of about 2%; and,
3. $e - \pi$ separation will be improved beyond what we have already accomplished [17].

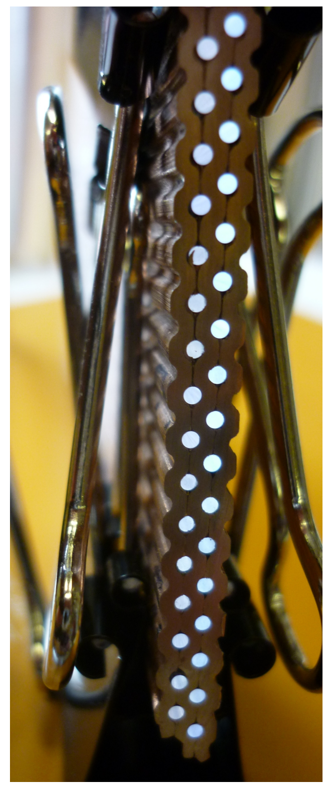

Figure 6: Sample of rolled Cu loaded with 1mm fibers.

The optical coupling between the fiber bundle and the PMT photocathode will be improved with light mixer boxes and other optical tricks.

These new rolling-forming techniques work well, but need to be perfected for the full-sized larger plates ($40 \times 40 \times 250$ cm^3). Precision is required since the cladding and buffer on each fiber is 10μm thick and layer-to-layer uniformity is important to avoid stresses on the fibers. In the Ames Lab, we have precision machined 22-cm wide rollers for a rolling machine with 100-ton capacity for the Cu-absorber sheets of SuperDREAM as a test, Fig. 6.

There are interesting differences between $\pi^{\pm}$-initiated and n/p-initiated hadronic showers. Conservation of baryon number results in a three-quark system that maintains it momentum and energy in the forward direction, and therefore leaves less energy available for the production of $\pi^0 \to \gamma\gamma$. Data in a quartz fiber calorimeter ($\eta \sim 0.2$) shows that the mean response for proton-initiated showers is 10% less than $\pi^{\pm}$-initiated showers [10](page 61) from 200-400 GeV.

The response is shown in [10](page 252) at 300 GeV, displaying both the lower mean response and narrower resolution for protons,

$$(\sigma/E)_{\mathrm{proton}} \approx 0.8\ (\sigma/E)_{\pi^-}.$$

The depth development also differs by 20% which may provide some discrimination in baryon/meson and additional discrimination in neutron/photon.

4 Project Summary and Deliverables

This one-year collaboration between the EIC community and the RD52 project will accomplish the following goals:

- Identify in detail how state-of-the-art hadronic calorimetry can enhance the EIC physics program
- Bring a full description of the performance capabilities of the DREAM concept to the EIC community. These performance characteristics (average performance and fluctuations) can then be incorporated into the EIC simulations, either in the form of semi-analytic parameterizations, or full shower simulations.
- Evaluate if desired performance characteristics and configurations for an EIC ZDC require more in-depth EIC-specific prototyping, simulation, and development.

5 Budget

Funds are requested for travel to the beam tests at CERN for direct participation of JLab and ODU in the data taking, and travel to a domestic collaboration meeting and/or BNL for all participants

A. Old Dominion University budget.

1. Three 10-day trips to CERN (2 people, 1–2 trips each):

	Per Trip	Total
a) airfare	$ 2000	
b) lodging, per diem	$ 1400	
Total CERN travel	$ 3400	**$10,200**

2. Two trips (one trip, 2 people) to US Collaboration meeting:

	Per Trip	Total
a) airfare	$ 500	
b) lodging, per diem	$ 460	
c) rental car (shared)	$ 100	
Subtotal	$ 1060	**$ 2120**

Total ODU Direct costs:	$12,320
Indirect Costs (53% of DC)	$ 6,360
Total ODU request	**$18,680**

B. Jefferson Lab budget

1. Two 10-day trips to CERN :

	Per Trip	Total
a) airfare	$ 2000	
b) lodging, per diem	$ 1400	
Subtotal	$ 3400	**$6800**

2. One trip to US Collaboration meeting:

a) airfare	$ 500
b) lodging, per diem	$ 460
c) rental car	$ 200
Subtotal collaboration	**$ 1160**

Total JLab Direct costs:	$7,960
Indirect Costs (51%)	$ 4,060
Total JLab request	**$12,020**

C. Iowa State University Travel:

One domestic trip: $1110 + 26% IDC. Total: **$1400**

Total Project Budget Request: $32,100

References

[1] Four progress reports to the SPS Council are available at `http://highenergy.phys.ttu.edu/dream/resources/proposals/`

a. `SPSC2014.pdf`

b. `/SPSC2013.pdf`

c. `/SPSC2012.pdf`, and

d. `/Progressreport.pdf`.

a. Gabriella Gaudio, John Hauptman and Richard Wigmans on behalf of the RD52 Collaboration, ‘Dual-Readout Calorimetry for High-Quality Energy Measurements,” Progress Report presented to the SPS Committee, 8 April 2014.

b. G. Gaudio and R. Wigmans, “Dual-Readout Calorimetry for High-Quality Energy Measurements,” Progress Report presented to the SPS Committee, 9 April 2013.

c. G. Gaudio and R. Wigmans, “Dual-Readout Calorimetry for High-Quality Energy Measurements,” Progress Report , 2 April 2012, CERN-SPSC-2012-014; SPSC-SR-100.

d. G. Gaudio and R. Wigmans, “Dual-Readout Calorimetry for High-Quality Energy Measurements,” Progress Report , 1 June 2011.

[2] L. B. Weinstein, E. Piasetzky, D. W. Higinbotham, J. Gomez, O. Hen and R. Shneor, Phys. Rev. Lett. **106**, 052301 (2011) [arXiv:1009.5666 [hep-ph]].

[3] Acosta, D., *et al.*, *Nucl. Instr. Meths.* **A308** (1991) 481.

[4] R. Wigmans, “Quartz Fibers and the Prospects for Hadron Calorimetry at the 1% Resolution Level,” *Proceedings of the 7th International Conference on Calorimetry in High Energy Physics*, Tucson(AZ), Nov. 9-14, 1997.

[5] Several other physicists had ideas related to dual-readout without understanding the critical role of compensation, WA1-Abramowicz, *et al.*. C. Milstene, A. Irwin, P. Mocket, D. Winn, and E. Ramberg are a few; from my private notes.

[6] N. Akchurin, *et al.*, “Hadron and jet detection with a dual-readout calorimeter,” *Nucl. Instr. and Meth.* **A 537** (2005) 537.

[7] D. Groom, “Simplification of the DREAM collaboration’s “Q/S method” in dual-readout calorimeter analysis,” arXiv:1208.1359v1 [phys.ins-det] 15 August 2012.

[8] Collider Detector R&D proposal (3-years): The SuperDREAM Project, R. Wigmans, DoE, 1 Apr 2012 - 31 Mar 2015

[9] Ames Laboratory, US Department of Energy, funded by Director’s Development Funds.

[10] "Calorimetry: Energy Measurement in Particle Physics," Richard Wigmans, Oxford University Press, 2000.

[11] Letter of Intent, 4th concept detector, at `http://www.4thconcept.org/4LoI.pdf`

[12] J. Hauptman, "Measurement of the neutron fraction event-by-event in DREAM," *Jour. of Physics* Conf. Series, **293** (2011) 012080, XIV Int'l Conf. on Calorimetry (CALOR10), Beijing, 10-14 May 2010.

[13] J. Hauptman, "Estimate of Neutrons Event-by-event in DREAM," *Jour. of Physics*, Conf. Series, **160** (2009) 012072; XIII Int't Conf. on Calorimetry (CALOR08).

[14] "Measurement of the contribution of neutrons to hadron calorimeter signals," N. Akchurin, *et al.*, *Nucl. Instr. Meth.* **A 581** (2007) 643.

[15] "Neutron signals for dual-readout calorimetry," N. Akchurin, *et al.*, *Nucl. Instr. Meth.* **A 598** (2009) 422-431.

[16] N. Akchurin, *et al.*, "Lessons from Monte Carlo simulations of the performance of a dual-readout fiber calorimeter," *Nucl. Instr. and Meth. in Phys. Res. A.* (accepted).

[17] N. Akchurin, *et al.*, "Particle identification in the longitudinally unsegmented RD52 calorimeter", *Nucl. Instr. and Meth. in Phys. Res.* **A 735** (2014) 120.